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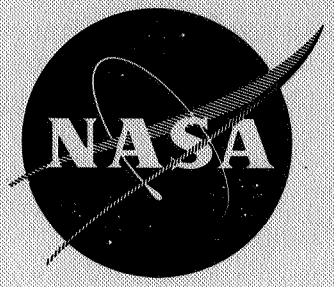

AN INVESTIGATION OF NEAR CRITICAL AND SUPER-CRITICAL BURNING OF FUEL DROPLETS

by

G. M. Faeth, D. P. Dominicis and D. R. Olson

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CONTRACT NGR 39-009-077

Mechanical Engineering Department
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First Annual Report

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September 30, 1967

Contract: NGR 39-009-077

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SUMMARY

The work described in this report considers the experimental combustion characteristics of liquid fuel droplets in air. The total pressure of the experiments ranged from atmospheric pressure to 2000 psi. This range was sufficiently broad to allow observation of near critical and super-critical droplet combustion. The fuels considered in the study were n-decane and n-hexadecane.

The test droplets were mounted upon either a quartz fiber or a thermocouple, contained within a small chamber that could be pressurized to the desired level. Ignition was accomplished either by momentarily directing a small flame toward the droplet or by placing a hot wire close to the droplet. The test chamber was carried within a free fall apparatus to allow testing under zero-gravity conditions. This technique eliminates the tendency of the droplet to fall from its support due to reduced surface tension near the critical point and simplifies the interpretation of the results by eliminating natural convection. Liquid temperature measurements and motion pictures were taken during the combustion process.

The conclusions of the study are as follows:

1. These results demonstrate the feasibility of this experimental technique for studies of high pressure droplet combustion.

2. With the flame ignitor, the combustion lifetime of the droplets decreased monotonically with increasing pressure. At higher pressures the gas flow induced by igniting flame caused shearing and breakup of the combustion zone.

3. With the hot wire ignitor, the ignition disturbance was reduced at high pressures. Under these conditions the lifetime reached a minimum near the critical pressure. At pressures somewhat above the critical pressure the lifetime increased and was roughly proportional to the cube root of pressure in accordance with prior theoretical predictions.

4. With increasing pressure, the temperature measurements indicated that a decane droplet spends a smaller fraction of its lifetime in the steady burning period (characterized by the droplet remaining at a constant "wet bulb" temperature). However, an approach to this condition, indicated by an inflection of the temperature trace, was observed at pressures as high as twice the critical pressure of the fuel. Above this pressure the temperature at the droplet location rose continuously, to values exceeding the critical temperature, throughout the combustion process.

5. It was found that there is a significant time interval between the end of the gasification of the droplet liquid and the end of combustion. This indicates that it is incorrect to interpret combustion lifetimes as gasification lifetimes under the conditions of this study.

6. For tests with the hot wire ignitor, liquid temperatures above the boiling point of the liquid were recorded at the lower test pressures. The possibility of excessive radiation from the hot wire as a cause of this behavior is under investigation at the present time.

INTRODUCTION

The wide application of liquid bipropellants in rocket technology has led to numerous studies directed toward the goal of developing rational design procedures for bipropellant combustion chambers. The recognition of the controlling influence of droplet evaporation on combustion chamber performance by Priem[1] represented a major step toward this goal. Further work by Priem and Heidmann[2] established a theoretical model of bipropellant spray combustion that gave a good estimation of measured combustor performance at moderate pressures.

Of central importance in the application of the Priem and Heidmann[2] technique is a good understanding of the combustion characteristics of individual droplets. With this in mind the overall objective of the present investi-

gation was to study the combustion characteristics of single fuel droplets in an oxidizing atmosphere at the high pressure levels encountered in rocket engine combustion chambers.

Of the previous work on droplet combustion, the earliest studies concentrated on the steady burning period of the droplet, i.e. the state where all the heat transferred to the droplet is utilized for the heat of vaporization of the evaporating material and the droplet temperature remains constant at its so-called wet bulb temperature. Under the assumption of quasi-steady burning at the wet bulb state, various formulas have been derived to calculate droplet burning rates[3-5]. On the whole, the predicted rates are in reasonable agreement with the results of laboratory experiments conducted at atmospheric pressure[4-7].

Later work, conducted by a number of investigators at the University of Wisconsin[8-10], considered droplet heat up, as well as the steady burning period. In these studies a quasi-steady analysis of transport rates was found to give an adequate prediction of droplet life histories, in the absence of combustion, in air at temperatures up to 620°F and total pressures in the range 1-4 atmospheres.

While there have been relatively few investigations of high pressure droplet combustion, there are two aspects of this problem that have received attention in the literature. The first, as pointed out by Williams[11] and Brzustowski[16], is that at high pressures certain aspects of the quasi-steady analysis of transport rates to droplets become questionable. This includes both the neglect of the finite normal velocity of the droplet surface and the transient adjustments of the boundary layer around the droplet to varying conditions at the droplet surface.

The second aspect, which has been considered by Wieber[12], is the possibility that at elevated pressures the droplet reaches its critical point before combustion is complete. Wieber's theoretical calculations of the approach of a droplet to its critical temperature employed the quasi-steady approximation. His results indicated that super-critical burning may be encountered in high pressure combustion systems such as rocket and diesel engines. For heptane, he found that the total pressure must be two to three times greater than the critical pressure before appreciable amounts of the droplet material remains when the critical point is reached.

Upon reaching its critical point, the droplet essentially becomes a puff of gas. Spalding[13] has theoretically considered this type of combustion by approximating the droplet vapor as an instantaneous point

source of fuel. The combustion process was represented by a flame surface approximation, i.e. a diffusion controlled flame with an infinitely thin reaction zone. This analysis has recently been modified by Rosner[14] to account for the finite dimensions of the puff of gas, however, these studies have not been verified experimentally.

Experimental investigations of single droplet burning have most often been conducted by observing a suspended droplet[4-10]. Employing this technique, Hall and Diederichsen[15] have studied droplet burning at elevated pressures. They obtained measurements of droplet lifetimes, following ignition, as a function of pressure and initial droplet diameter. Although this work considered pressures as high as twenty atmospheres, testing could not be extended into the near critical and super-critical burning regimes. This limitation was due to the reduction in the surface tension as the liquid approached the critical point which allowed the droplet to fall from its support at high pressures.

Recently, Brzustowski and Natarajan have studied the combustion of aniline droplets at pressures up to 815 psi, which is 44 psi above the critical pressure of aniline[17]. The fact that the droplets did not fall from their support during these tests indicates that the near critical burning regime was not reached. This might be anticipated from the n-heptane results of Reference (12), which indicates that higher pressures would be required before substantial amounts of super-critical burning could occur. Brzustowski and Natarajan made measurements of burning rate constants at pressures below 200 psi (the burning rate constant is defined as the rate of decrease of the square of the droplet diameter[17]) and burning lifetimes at higher pressures. Difficulties in obtaining clear silhouette photographs above 200 psi prevented measurements of burning rate constants in the high pressure region. It is noteworthy that Hall and Diederichsen[15] experienced similar difficulties at high pressures.

In summary, it appears that there are several problem areas in the prediction of droplet life histories, particularly in the near critical and super-critical regimes. The quasi-steady theories become questionable at high pressure and have not as yet received experimental confirmation under these conditions. Similarly, the super-critical burning theories have not been tested experimentally.

With these factors in mind, the objectives of the present investigation were as follows:

1. To conduct experiments on the combustion of individual fuel droplets at pressures sufficiently high so that observations can be made of near critical and super-critical combustion.

2. To compare the present quasi-steady and super-critical combustion theories with the experimental results and to make any necessary modifications of these theories in order to obtain good predictions of droplet life histories.

The first phase of the study, which is reported here, was devoted to the development of a suitable experimental apparatus and to preliminary experiments in the near critical and super-critical burning regimes. The experimental technique employed in the study consisted of observing the combustion of a supported droplet. In order to avoid the tendency of the droplet to fall from its support at elevated pressures, the tests were conducted under zero-gravity conditions in a free fall apparatus. This technique is similar to that first employed by Kamagai and Isoda[18,19].

The fuels considered in the bulk of the results to date were n-decane and n-hexadecane. The ambient environment was air at pressures in the range 14.2 - 2000 psia.

APPARATUS AND PROCEDURE

The test droplet was mounted either on a quartz fiber or on the junction of a thermocouple as illustrated in Figure 1. The quartz fibers were approximately .008 inch in diameter with a .014 inch diameter bead at the end to assist in supporting the droplet. The thermocouple junction was constructed of .003 inch diameter chromel-alumel wires with a bead at the junction of approximately .009 inch diameter. The droplet was mounted with a hypodermic syringe through the access hole in the chamber.

The droplet reaction chamber (Figures 1 and 2) was constructed of stainless steel and could be pressurized to the test pressure through the air inlet. The chamber was fitted with two 1 inch diameter quartz windows for back lighting and photographing the droplet. The interior volume of the chamber was roughly cylindrical in shape, 2-5/16 inches in diameter and two inches long.

Two different schemes were employed for igniting the droplet. The first consisted of momentarily directing a small hydrogen diffusion flame toward the droplet until it ignited. The hydrogen for the flame was stored in a small cylinder, maintained at a pressure somewhat above

the test pressure in the reaction chamber. The capillary flame was actuated by opening a solenoid valve in the line from the storage tank. A hot wire then ignited the flame which in turn ignited the droplet. The timing of the solenoid valve was such that the hydrogen flame was turned on as soon as the free fall period began. The flame was then shut off as soon as possible, after the droplet ignited, in order to minimize the disturbance of the droplet by the gas flow through the capillary tube. This droplet ignition method is essentially the same as that employed by Hall and Diederichsen[15].

In the second ignition scheme, the hydrogen flame was discarded and the hot wire was placed close to the droplet. Power was applied to the wire after the free fall period began in order to reduce the disturbance of natural convection from the wire. The heated wire then ignited the droplet. This scheme was superior to the hydrogen flame due to the fact that it was more reliable and caused much less disturbance of the droplet.

A schematic diagram of the overall arrangement of the apparatus in the free fall chamber is shown in Figure 3. A photograph of the apparatus appears in Figure 4. The free fall chamber is 8 inches in diameter and incorporates two full length doors to allow complete access to interior components.

The zero-gravity facility in this laboratory has a free fall distance of 16 feet which provides nearly a one-second test time. The test chamber is held in place by a pin mechanism which can be released by a pneumatic cylinder to start the free fall period. The shock of the fall is absorbed by a tub filled with chopped foam plastic. This system limits the maximum deceleration of the test chamber to 10 g's, which is in the normal range of operation of most mechanical and electrical components. Drag forces on the chamber cause a divergence from zero-gravity conditions, but this is very small for the velocities attained over a 16 foot free fall distance.

A small neon bulb, powered from a d.c. source in order to give a steady illumination, was used as the background light for the silhouette droplet photographs. This light was employed in order to obtain a measurement of the initial diameter of the droplet. For these measurements, the elliptical shape of the droplet was corrected to a sphere of equal volume as suggested by Kobayasi[6]. The background light was turned off prior to the start of the free fall period so that dark field photographs could be taken of the combustion process.

A Wollensack Fastair, 16 mm motion picture camera was employed for the photographs. The droplet was viewed from the camera location by a front surface mirror mounted near

the window of the reaction chamber. The camera speed was approximately 100 pictures per second. The camera incorporates an internal timing marker to allow a running calibration of film speed in order to provide time sequencing of the photographs. The film employed for the photographs was Kodak Tri-X negative, emulsion TXN 430.

Commercially pure, dry air in cylinders was employed to pressurize the droplet chamber. Filling and emptying the chamber was accomplished through a quick disconnect fitting. The gas pressure within the chamber was measured with a 0-3000 psi bourdon tube gage with 25 psi subdivisions for pressures above 100 psi. For pressures below 100 psi, a 0-100 psi laboratory test gage with 1/2 psi subdivisions was employed.

The output of the thermocouple junction was recorded on an oscillograph. The oscillograph galvanometers had a flat frequency response (5%) to 2200 hz. The motion picture film and the oscillograph record were synchronized by recording the current flow through the neon background light.

Once the droplet was mounted and the chamber pressurized, the operation of the apparatus was largely automatic through the use of a cycling timer and a dropping weight switch. The dropping weight switch consisted of a steel block that could slide down guide rods to actuate a number of knife blade switches. The block was held in its uppermost position by an electromagnet which could be de-energized to allow the weight to fall. This switch arrangement was employed for those functions which required accurate and reproducible time sequencing. This included actuating the hydrogen solenoid or the droplet hot wire and the release of the free fall chamber. The cycling timer was employed for less critical functions such as actuation of the background light, the electromagnet, recorder, camera, etc.

FLAME IGNITOR TESTS

For these tests the droplet was mounted on the quartz fiber and no temperature measurements were made. A typical film record taken from a test at low pressures is shown in Figure 5. This test consisted of an n-decane droplet burning in air at a total pressure of 114 psia.

In Figure 5, it is seen that the droplet ignites a short time after contact with the hydrogen flame. The combustion zone of the droplet has a teardrop shape indicating the presence of some convection. This convection is undoubtedly due to gas motion induced by the flow of hydrogen in the ignitor flame. While this effect persists throughout the burning process it does not appear that the droplet leaves the probe location.

A typical result at high pressures is shown in Figure 6. The conditions of this test were an n-decane droplet in air at 814 psia. Here it is seen that the gas motion induced by the ignitor flame causes a significant disturbance of the combustion process. The combustion zone becomes quite elongated and appears to drift away from the probe location toward the end of burning.

Measurements of the combustion lifetime of the droplets were made from the films. This lifetime was defined as the total time between ignition of the droplet and the end of luminosity of the flame. This definition is the same as that employed by Hall and Diederichsen[15].

Figure 7 shows the measured lifetimes as a function of pressure for n-decane droplets of a more or less fixed initial diameter (740 ± 50μ). Data taken from Hall and Diederichsen[15] for the same fuel and droplet size are also shown on the figure for comparison. The indicated critical pressure was calculated employing the Lyderson method[20].

Both sets of data show a continuously decreasing burning lifetime with increasing pressure. The present burning lifetimes are seen to be longer than those of Reference (15) at comparable conditions. This is probably due to the elimination of natural convection in the present experiment. The induced flow of the ignitor provides some flow, but this is much smaller than a natural convection flow at the same pressure. For example, when ignited under one-g conditions, the ignitor flame rose almost straight up rather than following the direction of the capillary tube as it does under zero-g conditions. Similarly, combustion photographs taken at comparable pressures under one-g conditions in References 15 and 16 show that the flame zone is much closer to the droplet than is the case for the present results (Figure 5), indicating stronger convection effects for the one-g testing.

Figure 8 shows combustion lifetimes for n-hexadecane (cetane). As before, the critical pressure indicated on the figure was calculated by the Lyderson method[20]. It is seen that the trends of this data with pressure and the magnitude of the lifetimes are comparable with the n-decane data.

While these tests were successful from the standpoint of allowing observations of droplet combustion at pressures substantially above the critical pressure of the fuel, the results were not completely satisfactory. First of all, the theoretical work of Spalding[13] and Rosner[14] indicates that the combustion lifetime should begin to increase with pressure at pressures somewhat above the critical pressure of the fuel. The present data exhibited no such tendency. Secondly, the photographs at

high pressures, Figure 6, indicated that the fuel sample was being strongly distorted and possibly broken up by the ignitor flow. While this type of breakup is undoubtedly present under combustion chamber conditions, and is important of itself, it presents real problems in the interpretation of the present data. These factors prompted the use of the hot wire ignitor as a way of reducing the disturbance cause by the ignition process. The results of these tests are discussed in the following section.

HOT WIRE IGNITOR TESTS

For these tests the droplet was mounted on a thermocouple junction and droplet temperatures were measured. A typical film record taken from a low pressure test is shown in Figure 9. This test condition consisted of an n-decane droplet burning in air at a total pressure of 64 psia. At ignition there is a spotty pattern of luminosity around the droplet, however, this pattern rapidly gives way to a relatively uniform combustion zone. It is seen that the distortion of the combustion zone is greatly reduced in comparison to the flame ignitor tests.

Combustion lifetimes from these tests, for n-decane, are shown plotted as a function of pressure in Figure 11. These lifetimes were corrected to represent a constant initial droplet diameter of 875μ since the actual spread of initial diameters (715-995μ) was broader than that employed in Figures 7 and 8. The correction that was used assumed a diameter squared relationship between the combustion lifetime and the initial diameter as follows:

$$t_c = (875/d)^2 \, t_m$$

where d is the initial droplet diameter in microns, t_m is measured combustion lifetime and t_c is the corrected (and plotted) lifetime. This type of correction was chosen since most of the individual processes of the droplet, heat up, steady burning, super-critical burning, etc. are proportional to diameter squared (References 3-5, 13-15).

The two darkened symbols at the high pressure end of the plot represent tests where combustion was not completed at the end of the free fall period. In these cases, the plotted value is the time between droplet ignition and the instant when the luminous zone was swept from view by the flow disturbance resulting when the chamber is stopped. Naturally, the actual lifetime must be somewhat longer than the plotted lifetime for these points.

It is obvious that the trends of this data, particularly at higher pressures, is quite different from that obtained with the flame ignitor. Here, rather than a continuously decreasing lifetime with increasing pressure, the lifetime increases with pressure at pressures somewhat above the critical pressure. These results provide further substantiation of the possibility of shearing and breakup of the fuel sample at high pressures when the flame ignitor was employed.

The theoretical results of Spalding[13] and Rosner[14] indicate that the burning lifetime should be proportional to the cube root of pressure in the super-critical combustion regime. The line shown in Figure 11 is drawn proportional to this prediction. It is seen that the high pressure data roughly follows the trend indicated by the curve, however, more data is required before an adequate evaluation of the theory can be made.

A disturbing feature of this data is that at low pressures the burning lifetime is shorter than that recorded for the flame ignitor, even though the initial droplet size was larger for this data and there was no large scale convective flow. The hot wire may have been the cause of this. During the tests with the hot wire ignitor the power input to the wire was held constant at all test conditions. Therefore, the wire glowed much brighter at low pressures due to the lower heat capacity, and thus cooling effect, of the surrounding air. Since the wire was quite close to the droplet, the higher wire temperatures could have caused a significant increase in the radiative heat transfer from the wire to the droplet at low pressures. This increased energy flow to the droplet would result in more rapid evaporation and a subsequently shorter droplet lifetime. The temperature data to be discussed below lends some support to this hypothesis.

Although temperature measurements in the droplet are subject to error due to temperature gradients during heat up[21], they do assist in rounding out the picture of the combustion process. A typical temperature record is shown in Figure 12 for a test with an n-decane droplet at 64 psia. The start of the time scale on this figure is arbitrary. Shown marked along the trace is the time when the glow of the hot wire was visible, the time of ignition and the time of the end of burning as obtained from the photographs of the droplet. The series of peaks at the start of the temperature trace is due to the noise signal generated when power is supplied to the hot wire.

The inflection of the temperature trace a short time after ignition was characteristic of most of the tests (see Figure 13 for other examples). This inflection apparently indicates the time when the presence of the

flame has propagated to the thermocouple location. Some time later, the temperature begins to level out at the "wet bulb" temperature and the so-called steady burning period follows. At the end of this period, after all the liquid has evaporated, the temperature begins to rise again. Finally, after some delay, the combustion process is completed.

Qualitatively, this behavior is in accord with the model proposed by Spalding[13], i.e., combustion ends some time after gasification of the droplet is completed. However, the length of the time between the end of gasification and the end of combustion was surprisingly long evan at low pressures (roughly 40% of the total lifetime for the test of Figure 12). Quite clearly, this result shows that it is incorrect to interpret the combustion lifetimes of Figure 11 as the time required to gasify the droplet over any portion of the pressure range.

Figure 13 shows temperature traces obtained over a range of pressures for n-decane. The critical temperature indicated on the figure was calculated by the Lyderson method[20]. The time scale on this figure is plotted from the time of ignition.

The plots show a progressive reduction in the length of the steady burning period with increasing pressure. For the test at 1100 psi there is no evidence of an approach to a wet bulb temperature. In this case, the temperature recorded by the thermocouple increases steadily throughout the combustion process. The test at 514 psia shows an inflection of the temperature trace indicating that there is still some approach to a wet bulb state at this condition even though the total pressure is above the critical pressure. This type of inflection was still observed at 664 psia, but was no longer evident at 814 psia. It is also notable that the rate at which the droplet temperature rises appears to increase as the total pressure is increased. Another characteristic of the results is that the liquid temperature is higher at ignition as the test pressure is increased.

In order to further summarize the temperature measurements, a plot of the maximum measured liquid temperatures was constructed as shown in Figure 14. For this plot, the maximum liquid temperature was taken to be the "wet bulb" temperature where this condition was clearly defined, e.g., for a plot like T-33 in Figure 13. For plots like T-20, the maximum temperature was taken to be the value at the inflection of the temperature trace. No data of this type is shown above 664 psia, since, as noted previously, no inflection of the temperature trace was observed above this pressure. The plot of saturated liquid temperatures as a function of pressure

(vapor pressure curve) shown on this figure was obtained from a Cox chart given in Reference (22).

It is seen that the maximum liquid temperature increases as the total pressure is increased and then begins to level out as the critical temperature is approached. However, it is quite disturbing that the maximum liquid temperature is substantially above the boiling point at the lower pressures. This condition is not possible unless the thermocouple was preferentially heated by radiation from the hot wire or conduction from the combustion zone along the thermocouple wires. The excessive heating of the hot wire at low pressures lends some support to the idea that radiation may be the factor responsible for this behavior. This possibility is under investigation at the present time. Until this question is resolved, it is suggested that the temperature magnitudes indicated on the figures be treated with caution, although the general characteristics of the temperature traces appear realistic.

REFERENCES

L. Priem, R. J., "Propellant Vaporization as a Criteria for Rocket Engine Design: Calculations of the Length to Vaporize a Single N-Heptane Drop," NACA TN 4098, 1957.

2. Priem, R. J. and Heidmann, M. F., "Propellant Vaporization as a Design Criteria for Rocket Engine Combustion Chambers," NASA Technical Report R-67, 1960.

3. Spalding, D. B., "The Combustion of Liquid Fuels," Fourth Symposium (International) on Combustion, Williams and Wilkins, Baltimore, 1953, pp. 847-864.

4. Godsave, G. A. E., "Studies of the Combustion of Drops in a Fuel Spray - The Burning of Single Drops of Fuel," Ibid, pp. 818-830.

5. Hottel, H. C., Williams, G. C. and Simpson, H. C., "Combustion of Droplets of Heavy Liquid Fuels," Fifth Symposium (International) on Combustion, Reinhold, New York, 1954, pp. 101-129.

6. Kobayasi, K., "An Experimental Study of the Combustion of a Fuel Droplet," Ibid, pp. 141-148.

7. Bolt, J. A. and Saad, M. A., "Combustion Rates of Freely Falling Drops in a Hot Atmosphere," Sixth Symposium (International) on Combustion, Reinhold, New York, 1956, pp. 717-725.

8. El Wakil, M. M., Uyehara, O. A. and Myers, P. S., "A Theoretical Investigation of the Heating Up Period of Injected Fuel Droplets Vaporizing in Air," NACA TN 3179, May 1954.

9. El Wakil, M. M., Priem, R. J., Brikowski, H. J., Myers, P. S. and Uyehara, O. A., "Experimental and Calculated Temperature and Mass Histories of Vaporizing Fuel Drops," NACA TN 3490, January 1956.

10. Borman, G. L., El Wakil, M. M., Uyehara, O. A. and Myers, P. S., "Graphs of Reduced Variables for Computing Histories of Vaporizing Fuel Drops and Drop Histories Under Pressure," NACA TN 4338, September 1958.

11. Williams, F. A., "On the Assumptions Underlying Droplet Vaporization and Combustion Theories," J. Chem. Phys., Vol. 33, July 1960, pp. 131-144.

12. Wieber, P. R., "Calculated Temperature Histories of Vaporizing Droplets to the Critical Point," AIAA J., Vol. 1, December 1963, pp. 2764-2770.

13. Spalding, D. B., "Theory of Particle Combustion at High Pressures," ARS J., Vol. 29, November 1959, pp. 828-835.

14. Rosner, D. E., "On Liquid Droplet Combustion at High Pressures," AIAA J., Vol. 5, January 1967, pp. 163-166.

15. Hall, A. R. and Diederichsen, J., "An Experimental Study of the Burning of Single Drops of Fall in Air at Pressures up to Twenty Atmospheres," Fourth Symposium (International) on Combustion, Williams and Wilkins, Baltimore, 1953, pp. 837-846.

16. Brzustowski, T. A., "Chemical and Physical Limits on Vapor-Phase Diffusion Flames of Droplets," Can. J. Chem. Eng., Vol. 43, February 1965, pp. 30-35.

17. Brzustowski, T. A. and Natarajan, R., "Combustion of Aniline Droplets at High Pressures," Can. J. Chem. Eng., Vol. 44, August 1966, pp. 194-201.

18. Kumagai, S. and Isoda, H., "Combustion of Fuel Droplets in a Falling Chamber," Sixth Symposium (International) on Combustion, Reinhold, New York, 1956, pp. 726-731.

19. Isoda, H. and Kumagai, S., "New Aspects of Droplet Combustion, Seventh Symposium (International) on Combustion, Butterworths, London, 1958, pp. 523-531.

20. Reid, R. C. and Sherwood, T. K., The Properties of Gases and Liquids, McGraw-Hill, New York, 1958, pp. 6-25.

21. Hall, A. R., "Experimental Temperature Gradients in Burning Drops," Seventh Symposium (International) on Combustion, Butterworths, London, 1958, pp. 399-407.

22. Perry, J. H. (ed.), Chemical Engineers' Handbook, McGraw-Hill, New York, 1950, pp. 153-166.

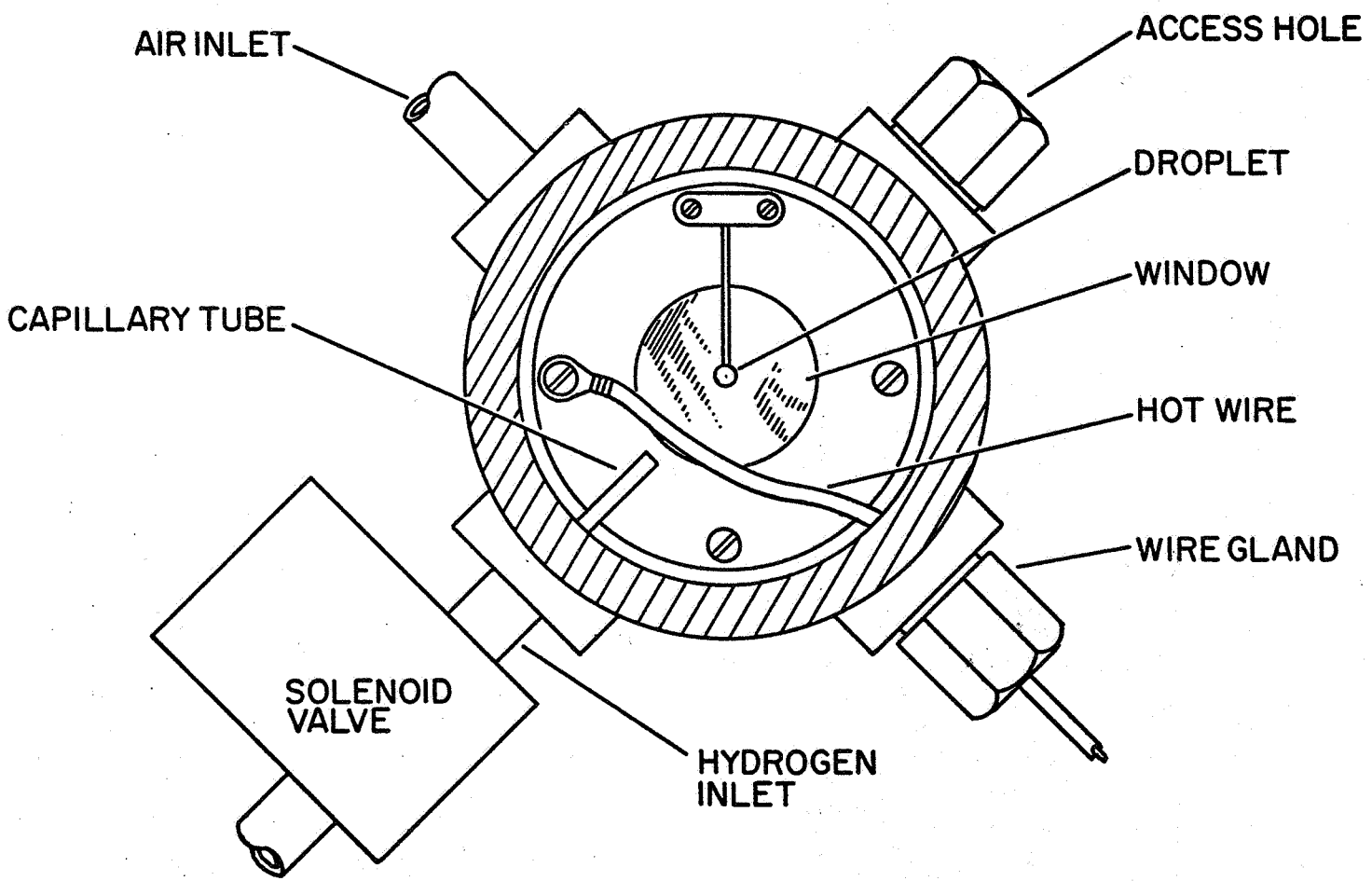

FIG. 1 SKETCH OF THE DROPLET CHAMBER

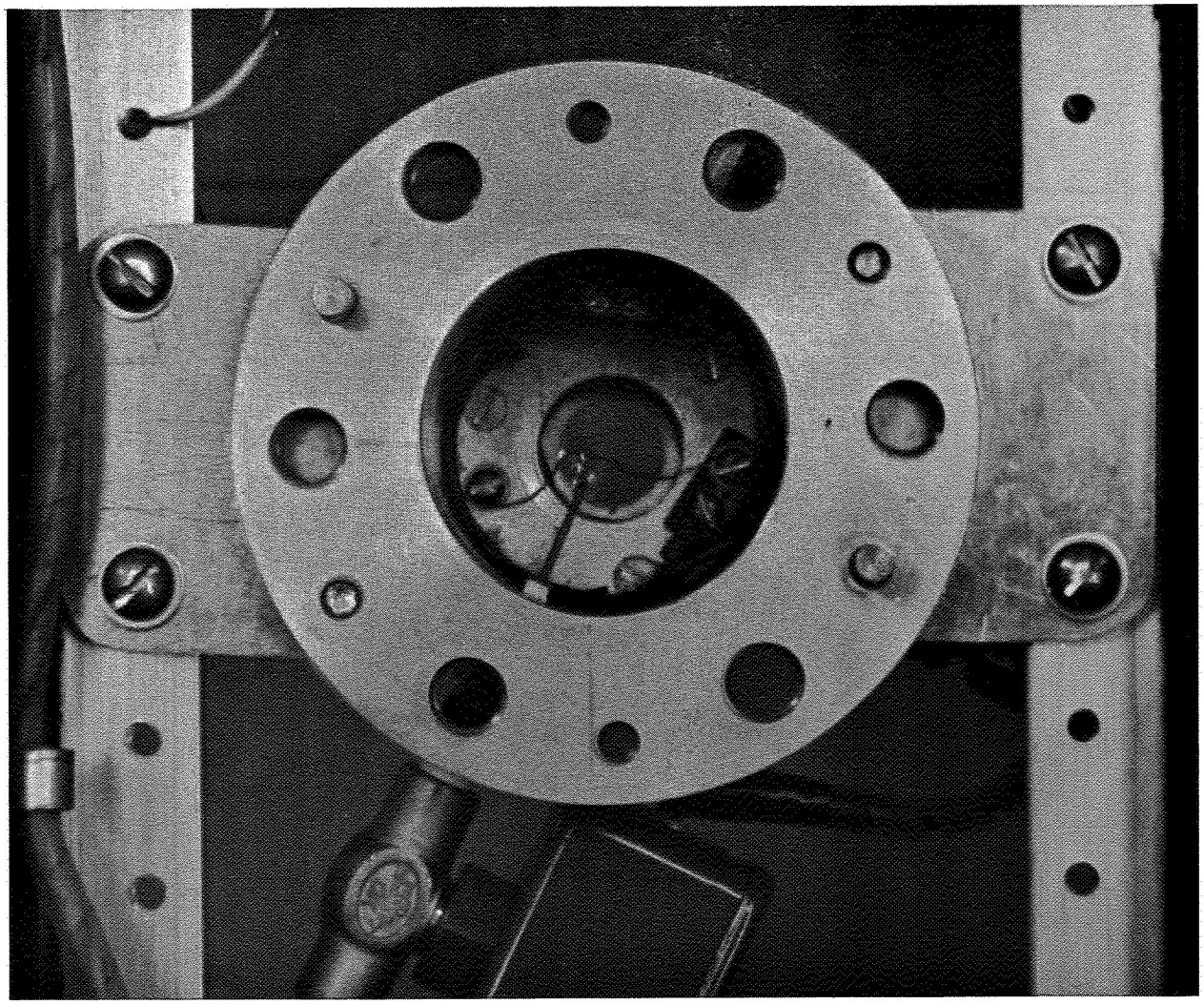

FIG. 2 PHOTOGRAPH OF THE DROPLET CHAMBER

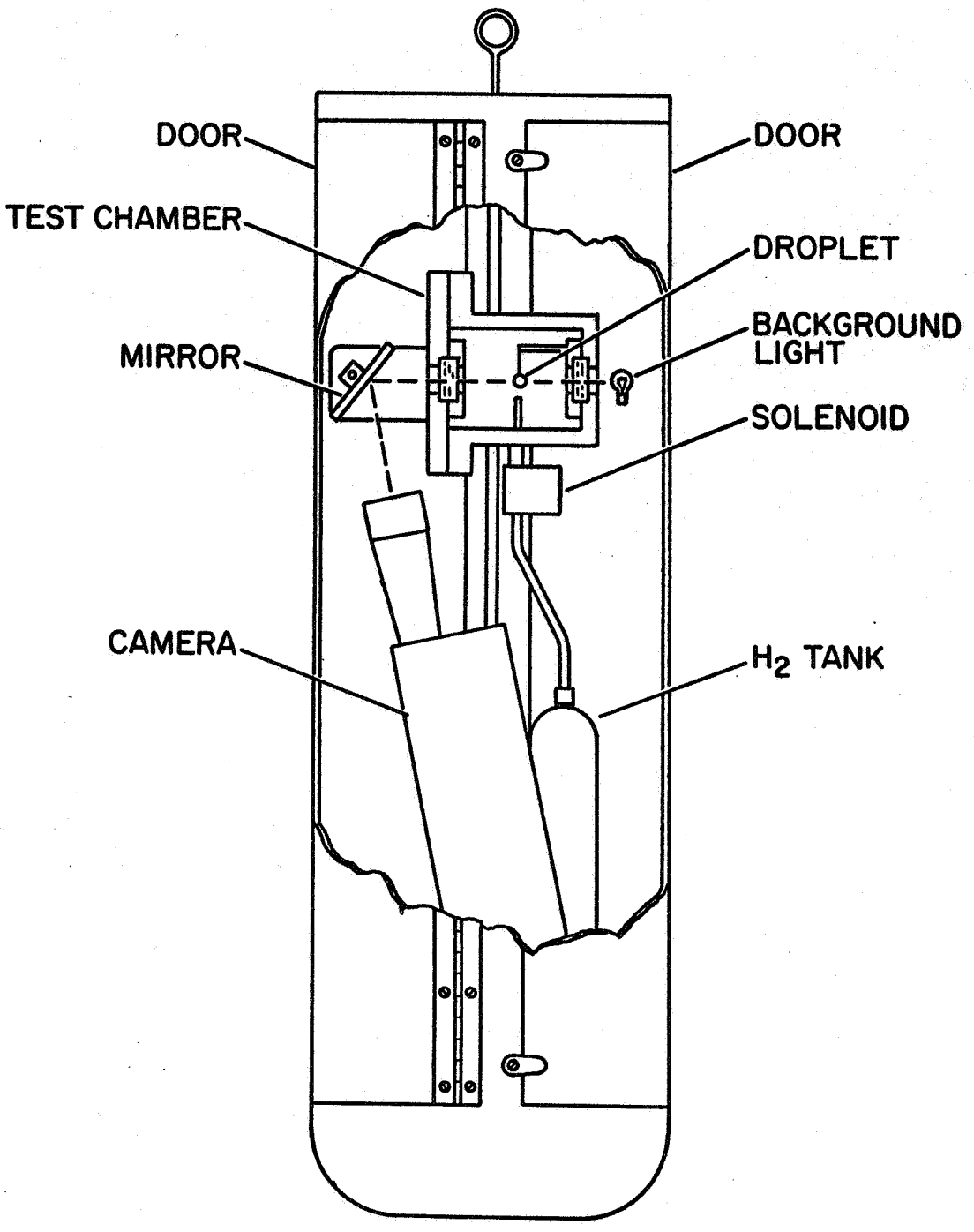

FIG. 3 SKETCH OF THE FREE FALL CHAMBER

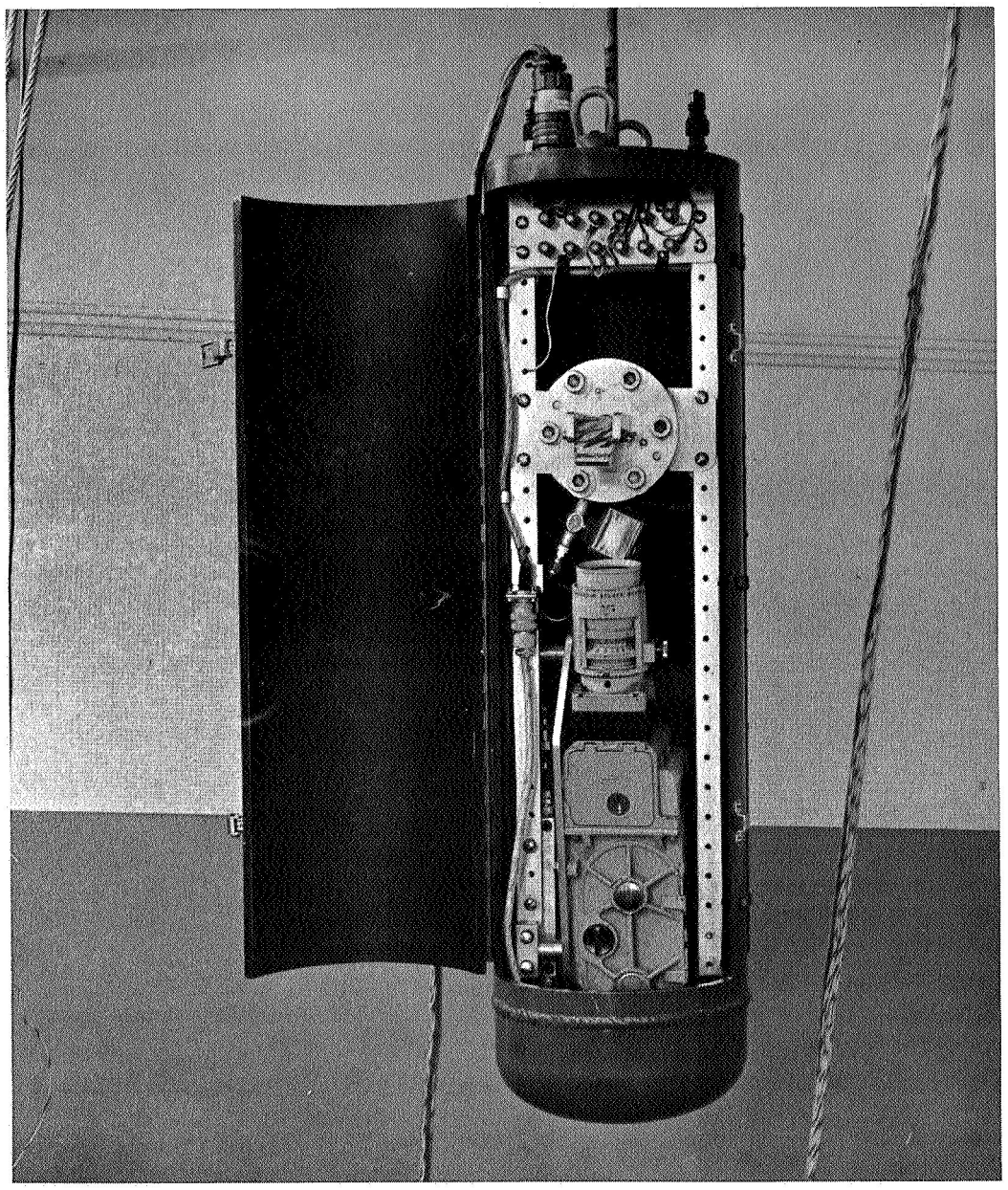

FIG. 4 PHOTOGRAPH OF THE FREE FALL CHAMBER

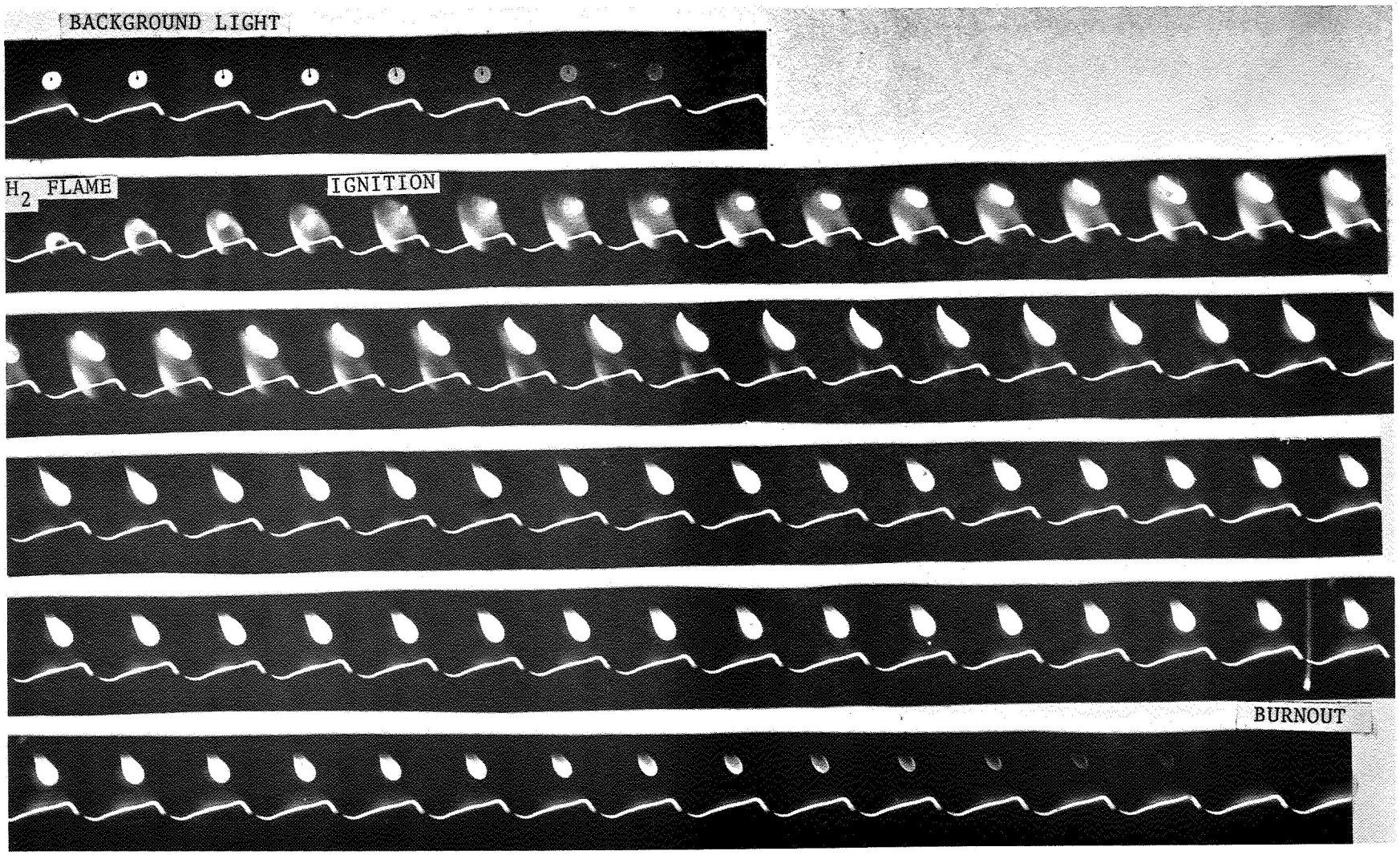

FIG. 5 COMBUSTION AT LOW PRESSURE (114 PSIA) WITH THE FLAME IGNITOR

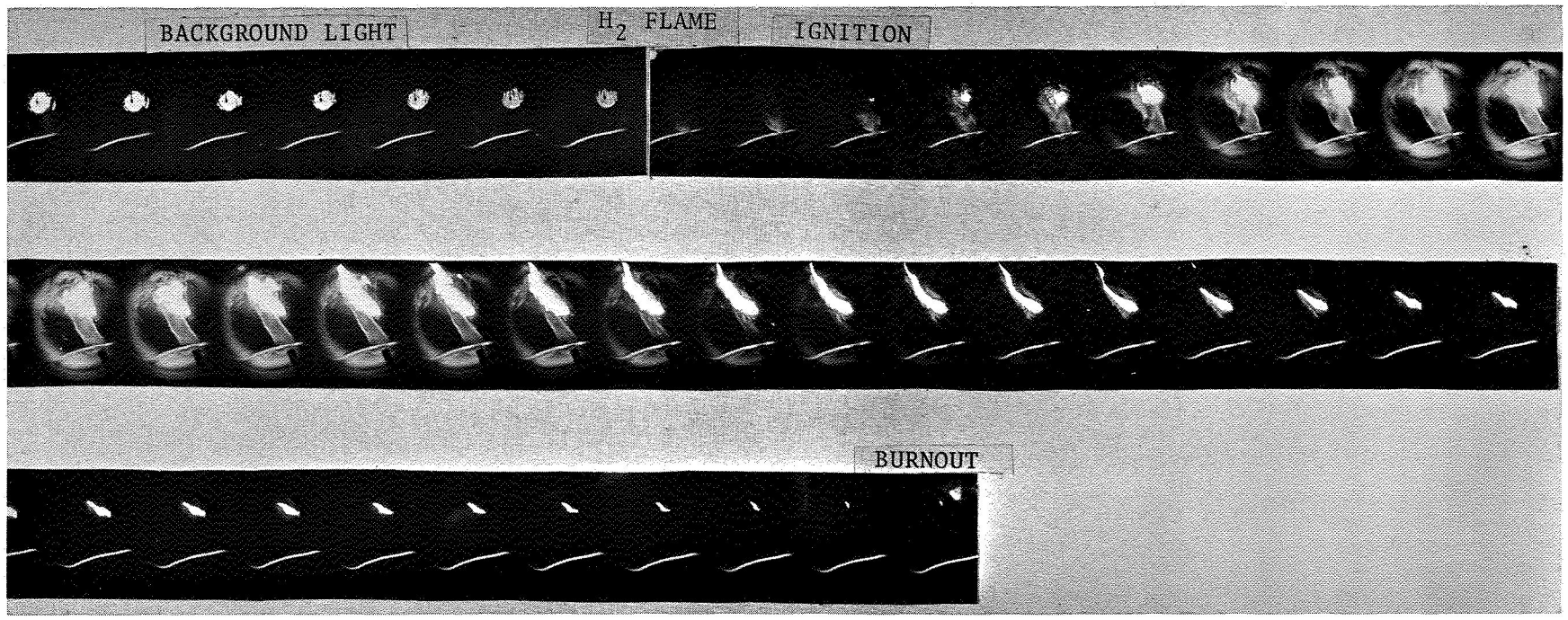

FIG. 6 COMBUSTION AT HIGH PRESSURE (814 PSIA) WITH THE FLAME IGNITOR

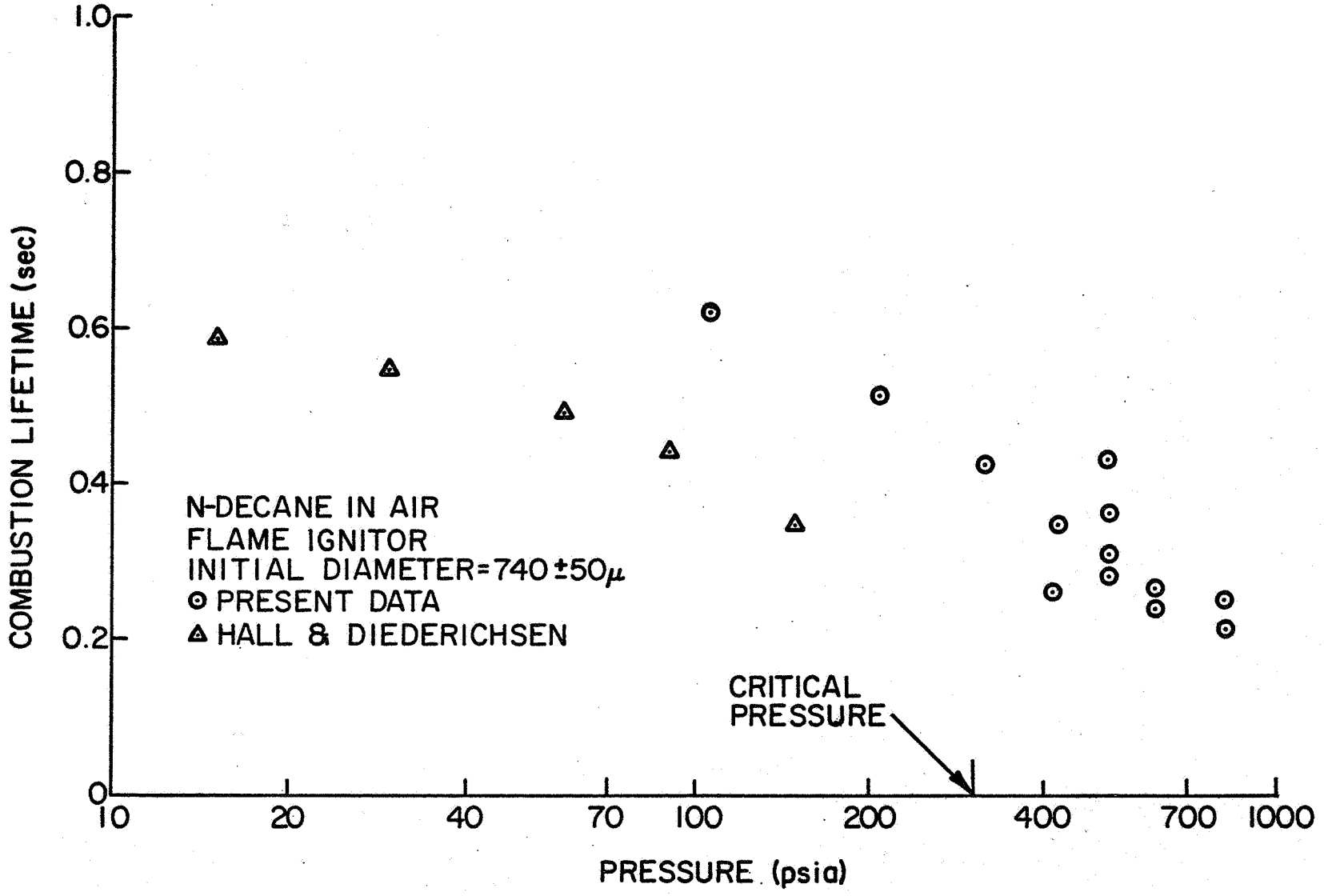

FIG. 7 COMBUSTION LIFETIME OF N-DECANE IN AIR-FLAME IGNITOR

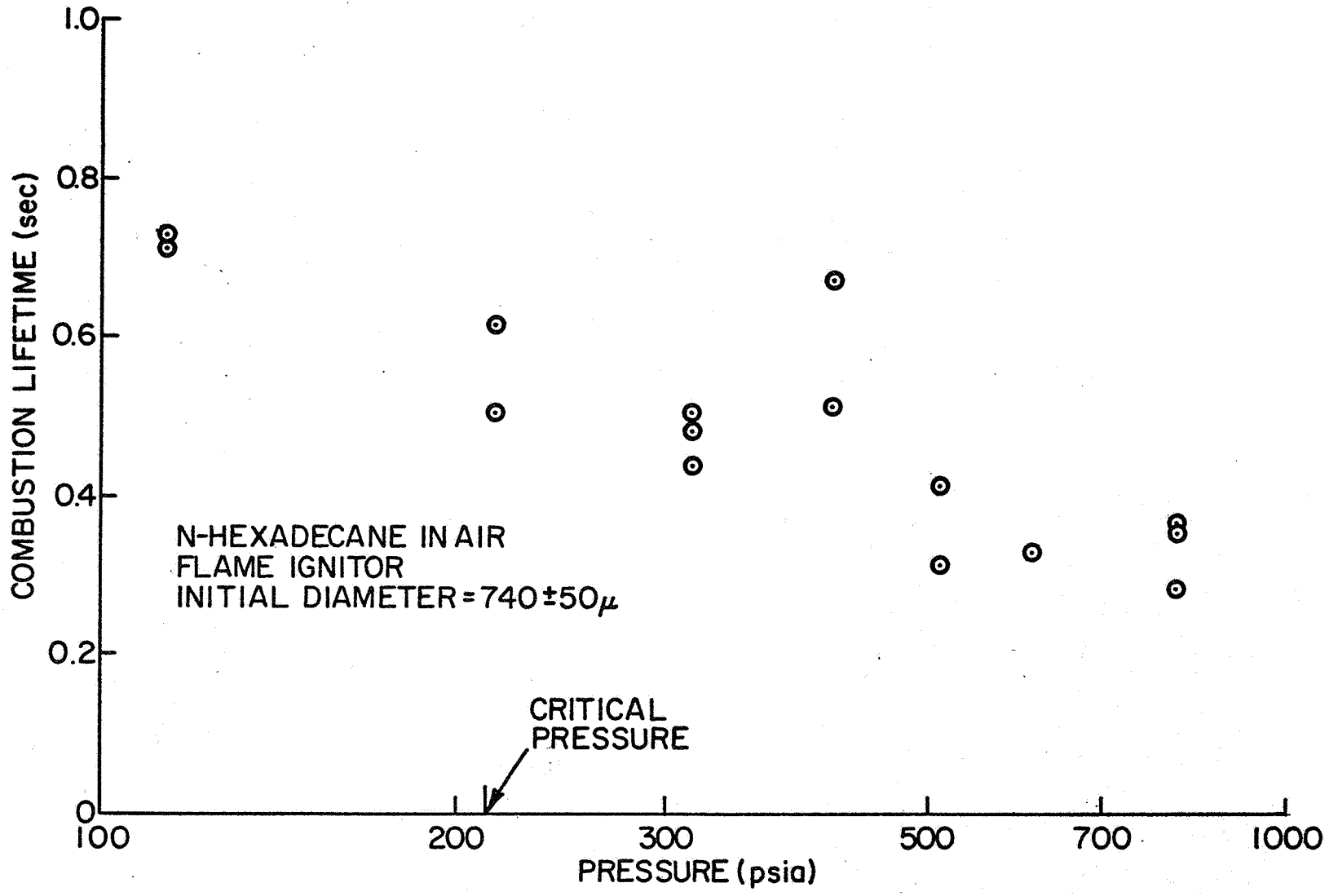

FIG. 8 COMBUSTION LIFETIME OF N-HEXADECANE IN AIR-FLAME IGNITOR

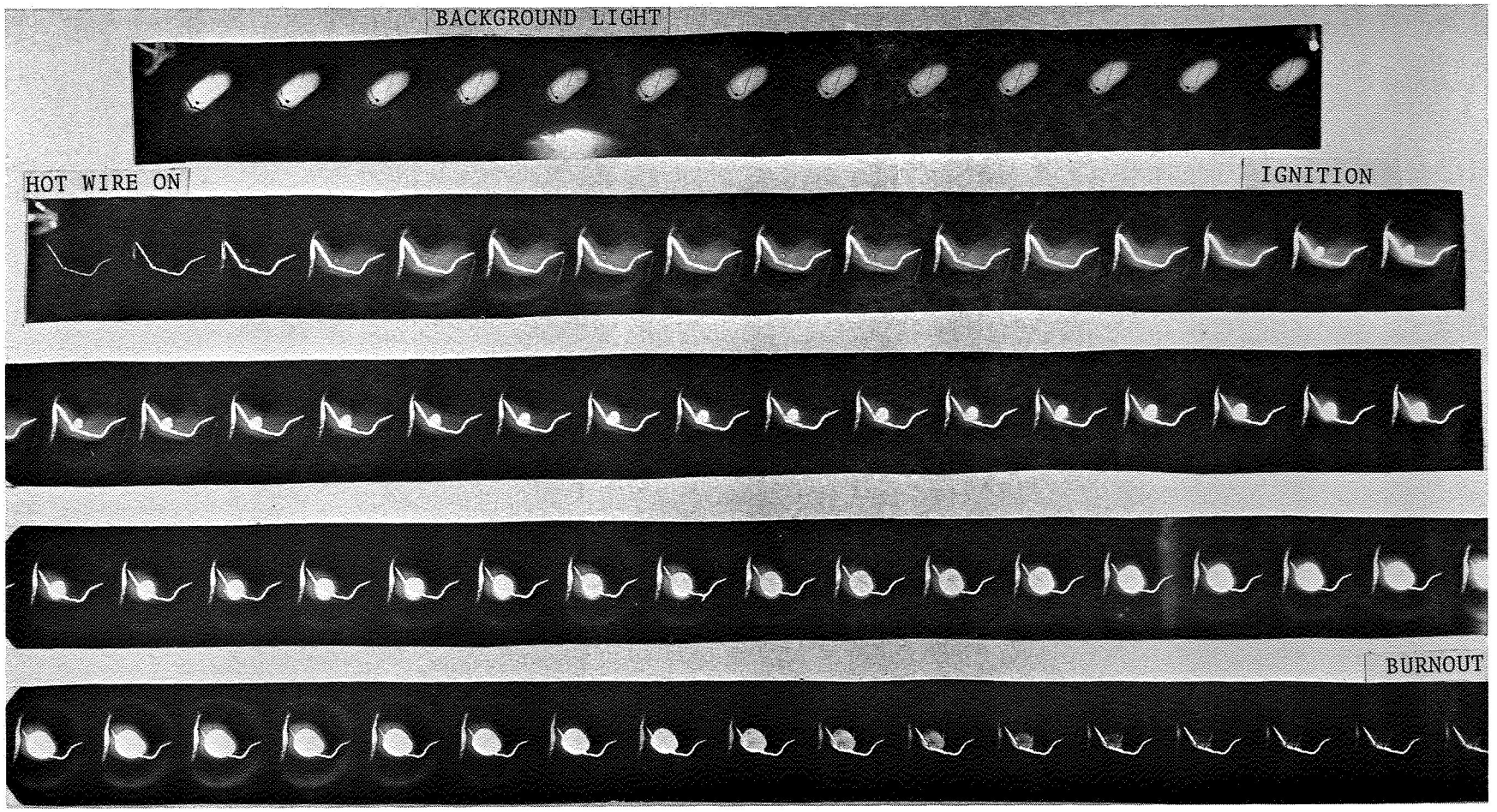

FIG. 9 COMBUSTION AT LOW PRESSURE (64 PSIA) WITH THE HOT WIRE IGNITOR

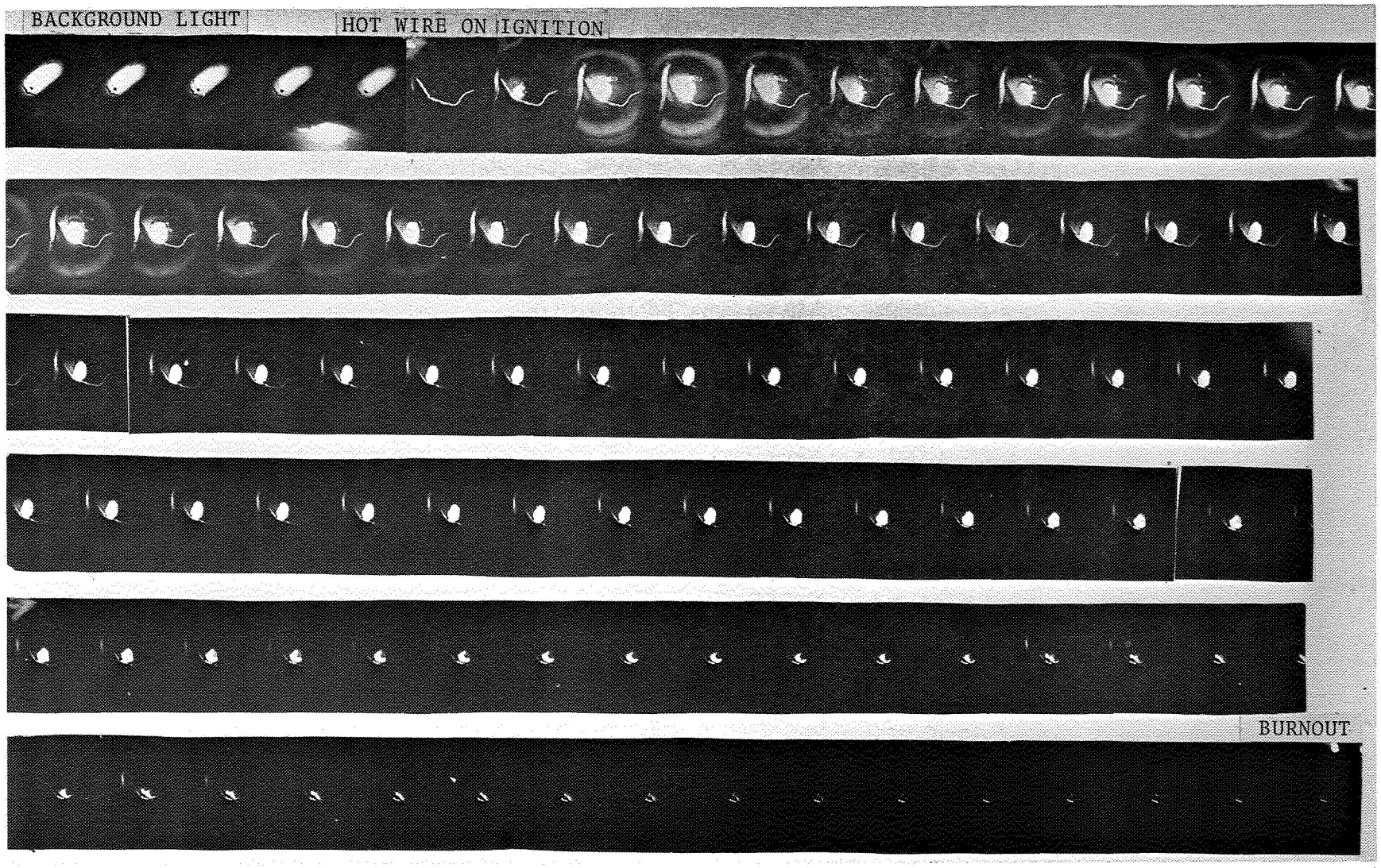

FIG. 10 COMBUSTION AT HIGH PRESSURE (814 PSIA) WITH THE HOT WIRE IGNITOR

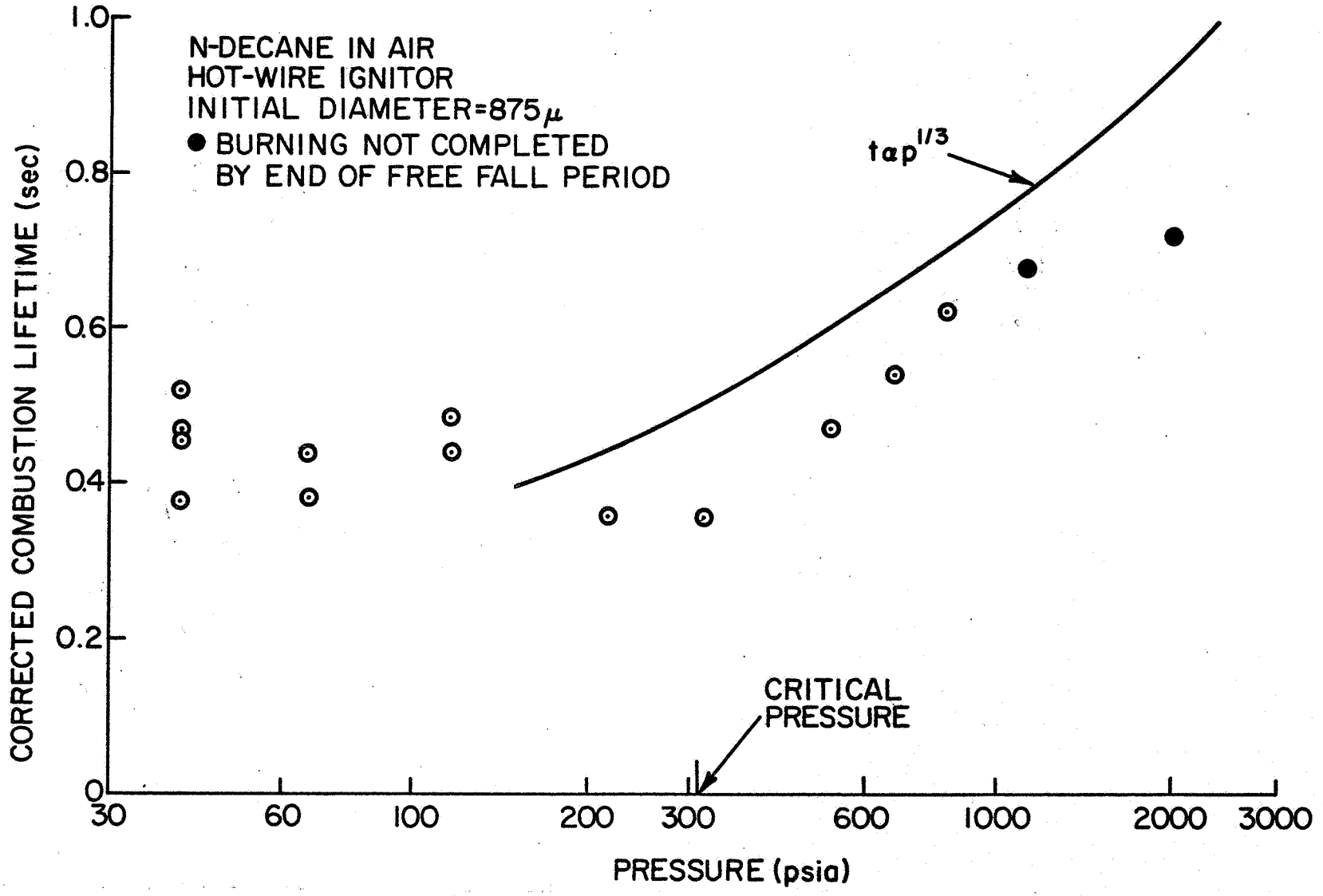

FIG. 11 COMBUSTION LIFETIME OF N-DECANE IN AIR-HOT WIRE IGNITOR

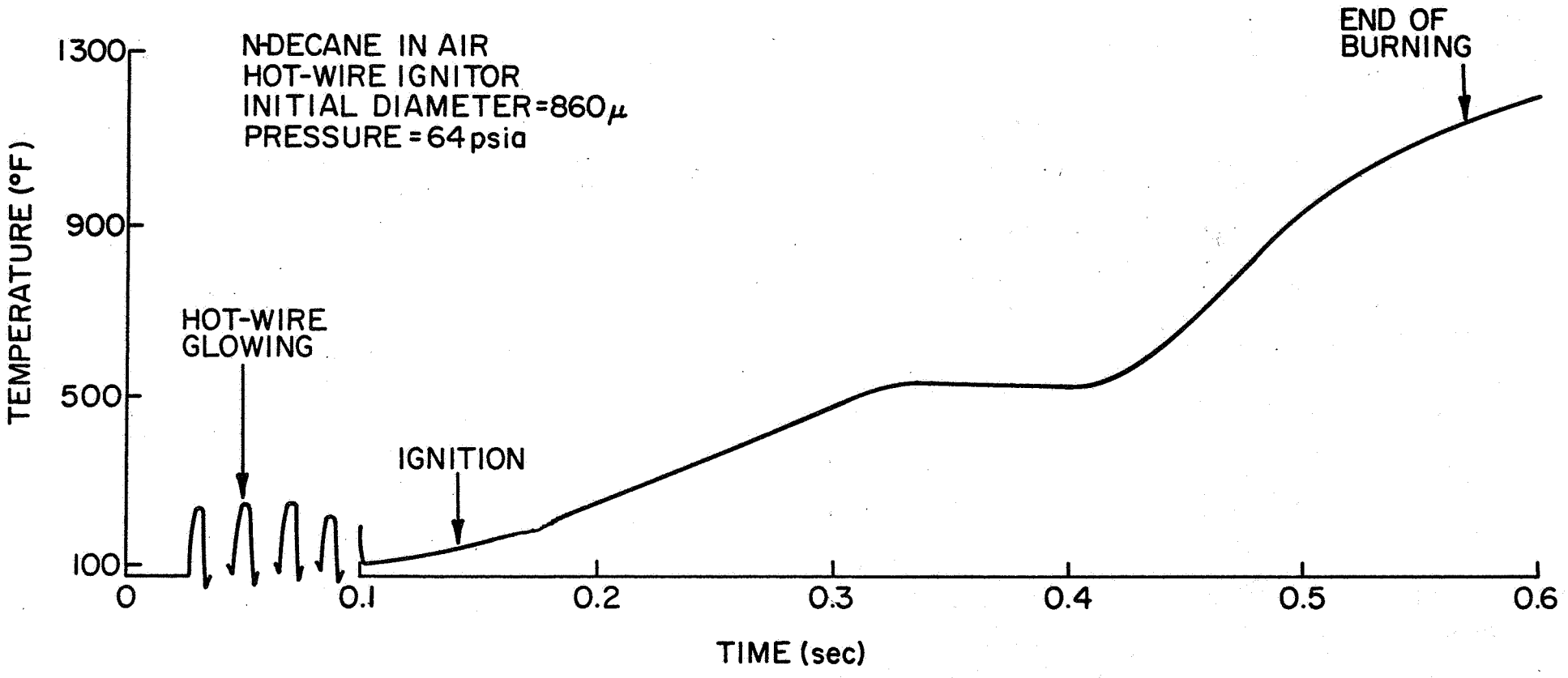

FIG. 12 TYPICAL TEMPERATURE RECORD

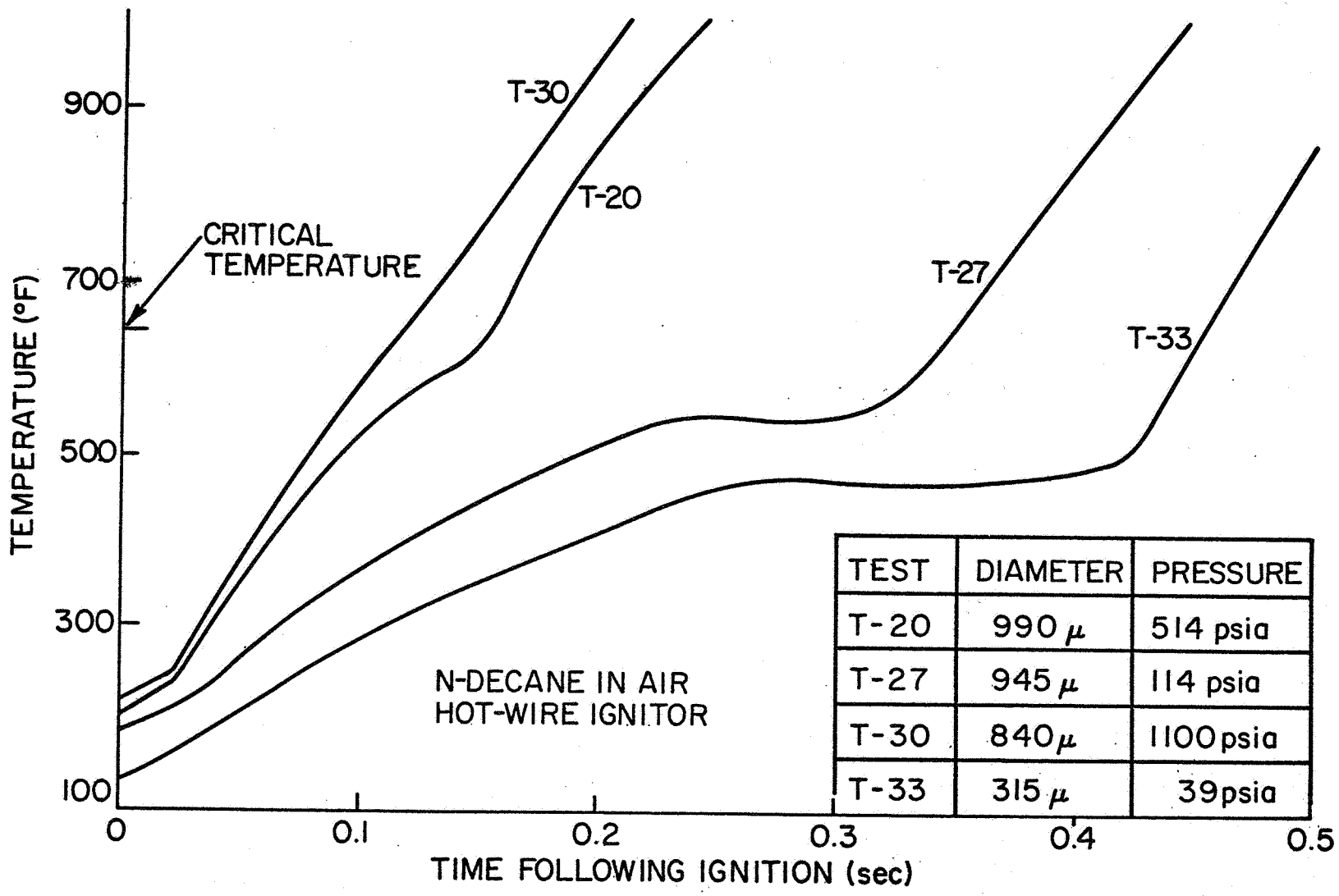

FIG. 13 DROPLET TEMPERATURE MEASUREMENTS AT VARIOUS PRESSURES

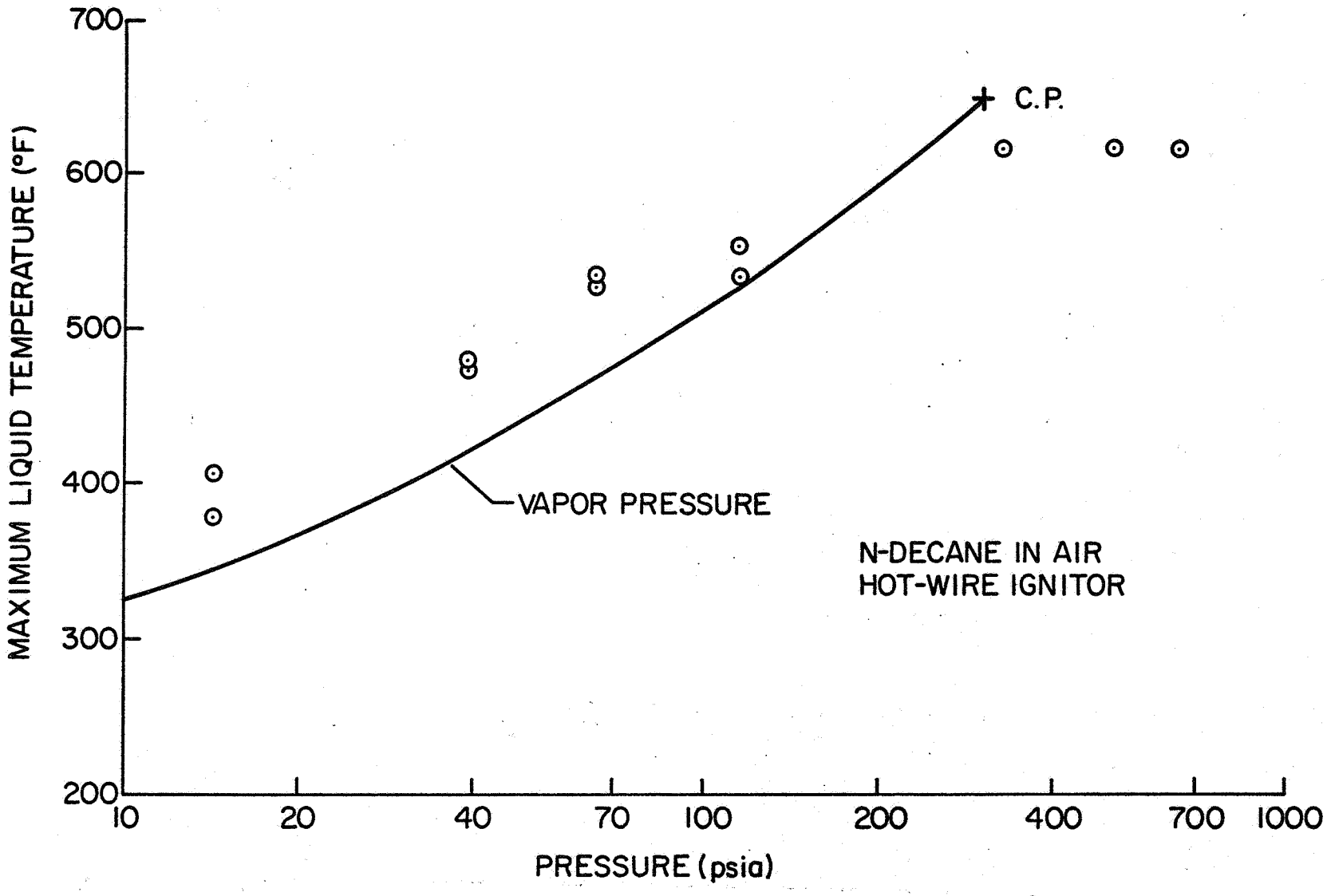

FIG. 14 MAXIMUM LIQUID TEMPERATURES AS A FUNCTION OF PRESSURE

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